Quantum computing and single-qubit measurements using the spin filter effect

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Abstract

Many things will have to go right for quantum computation to become a reality in the lab. For any of the presently-proposed approaches involving spin states in solids, an essential requirement is that these spins should be measured at the single-Bohr-magneton level. Fortunately, quantum computing provides a suggestion for a new approach to this seemingly almost impossible task: convert the magnetization into a charge, and measure the charge. I show how this might be done by exploiting the spin filter effect provided by ferromagnetic tunnel barriers, used in conjunction with one-electron quantum dots.

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I. QUANTUM COMPUTING

In its initial development, quantum computing seemed remote from the concerns of solid state or magnetic physics. It emerged initially, in the early 80s, as an abstract concept for computation that was studied by theoretical physicists concerned with the foundations of quantum theory; by the late 80s, it began to be of interest also to a small group of theoretical computer scientists. As Rolf Landauer has said, these theorists were much more interested in Hamiltonians and state vectors than in devices.

But the discoveries of the computer scientists, notably that of Peter Shor in 1994 [1], showed that quantum computing cannot be ignored as a future technology. If the bits of a computation can be embodied in quantum two-level systems (qubits) that would exist and be manipulated as coherent quantum states, the rules of computation become different; some calculations which will always be intractable on an "classical" computer are possible, and perhaps ultimately easy, on a quantum one [2].

It is by now pretty clear what requirements must be fulfilled for a particular quantum system to realize a quantum computer [3], and we can see now that there is the potential for achieving the necessary conditions in the solid state. These rules have been explored in detail elsewhere [4], but very briefly they may be summarized as follows. A simple quantum system must be available with a small number of discrete quantum states (ideally two to represent the qubit); it must be possible to assemble many such qubits and controllably couple and uncouple them with a repertoire of time-dependent Hamiltonians which accomplish the action of logic gates; the states of these qubits must have high quantum coherence, meaning that the state's decoherence time (during which the state entangles significantly with quantum states in the environment) must be at least 1000 times longer than the time to execute a logic gate; it must be possible to set these qubits into their ground state initially; and it must be possible to measure, reliably and quickly, the state of each qubit individually.

Much could be said about the quest to satisfy all these requirements. Efforts are underway to create simple quantum computer gates in many areas of experimental physics:

in atomic spectroscopy, in cavity quantum electrodynamics, in nuclear magnetic resonance on organic molecules, and in ion traps. A description of all of these would take me outside the scope of the present article, but I would mention one point on which these diverse areas intersect with the subject of this conference: in the majority of cases, the qubit is realized by a spin degree of freedom. This choice leads to very readily satisfying a few of the criteria for realizing quantum computation–for one thing, one obtains automatically a well defined two level system (for spin 1/2 degrees of freedom), and in addition, it is often the case that this degree of freedom interacts quite weakly with the environment, and thus has a long decoherence time.

Thus, the thinking that we [5] and others [6] have been doing about the potential solid-state implementations of quantum computers have also focussed on spin degrees of freedom. (This thinking has not been exclusively confined to spin; I will not touch here on qubits based on superconducting degrees of freedom [7] or quasiparticle excitations of an anyonic system [8]). Of course, we have had a long history of thinking about quantum effects in the dynamics of the magnetization of small magnetic particles and magnetic molecules. But this is actually not a good precedent for quantum computation either, as our focus for many years was on *macroscopic* magnetic effects [9], either MQT (tunneling) or MQC (coherence).

While it has been very fascinating that large systems can show any quantum effects at all, they are not particularly good candidates for quantum computing, since, being macroscopic, they interact readily with degrees of freedom in the environment. Thus, they do not show the very high degree of quantum coherence that is desirable for qubits in a quantum computer. I would not say, however, that by going over to microscopic magnetic degrees of freedom that the problems of achieving quantum computation become much easier; indeed, the proposals that are presently on the table involve tremendous extensions beyond the current experimental state of the art.

But, some consensus seems to be developing about a likely path for solid state quantum computing with spins. At least, two serious proposals that are on the table [5,4,6], starting from two very different points of view, have many elements in common. In both, the spin

of a single electron confined to a localized orbital state is used for quantum computation. In the Loss-DiVincenzo proposal the confinement is produced by a quantum dot deep in the Coulomb blockade regime; in the Kane scheme, the electron is confined in the bound state of a shallow donor, P in Si. (The proposals differ in that in the Kane proposal, the nuclear spin of the P is also employed as a qubit.) In both, quantum logic gates are achieved by voltage gates which manipulate the shape of the electron orbital, changing the overlap of the electron wavefunctions on neighboring quantum dots (or P impurities). Both need effective local magnetic fields to achieve spin precession of individual selected spins: Loss and DiVincenzo envision that small local fields are applied directly, Kane imagines changing the effective (Overhauser) field arising from the hyperfine nuclear-electronic coupling by distorting the electron orbital.

II. SINGLE-SPIN MAGNETOMETRY

And, both proposals require that quantum measurements be made at the single-spin level, and this will be the subject of the rest of this essay. It may seem maddeningly glib for theorists to pronounce, "the experimentalists shall measure magnetization at the one-Bohr-magneton level," and expect it to be done. Believe me, we have little choice; achieving quantum computation requires no less, much as we wish that it would. This theorist, at least, has observed with interest over the years the Herculean efforts that have been made by experimentalists to achieve ever more sensitive magnetometers, and recalls the landmark achievements in SQUID design which made it possible to push sensitivities down to 10^5 μ_B [9].

How, then, are we to do five orders of magnitude better? Of course, the experimentalists have not been inactive on this front, many have been questing towards this holy grail of single-quantum sensitivity. Rugar and his collaborators [10] have pushed closer than anyone else to arrive at this point by mechanical detection means (using a magnetic force microscope). But the work has been very hard, and they have not quite measured a single spin

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yet. Optical methods would seem to offer another approach–it is indeed by optical detection that single-atom measurements can be done in atomic physics–and the near-field optical techniques of Moerner [11] and of Gammon and coworkers [12] would seem to point the way towards another method of interrogating single quanta. I will be very interested if this technique can be pushed to see single spins separated on the tens-of-nanometers scale.

But in this essay I want to give some details of another completely different approach which we have proposed [5,4], largely inspired by the mindset of quantum computing, for achieving single-spin magnetometry by purely electrical means. The idea which we bring over from quantum computing to provide a new approach to this problem is that of coherent transfer of a quantum state from one embodiment to another. If it is possible to turn on and off the right kind of Hamiltonian between two physically different qubits A and B, then it is possible to swap the states of these two objects:

$$|\psi\rangle_A \otimes |0\rangle_B \overset{swap}{\to} |0\rangle_A \otimes |\psi\rangle_B. \tag{1}$$

In quantum computing an interaction which performs this function is referred to as a "swap gate." It is quite trivial from the point of view of computing (it just moves bits around, it doesn't actually perform any 'useful' logic operation on them), but it can mean something quite important for the measurement problem. Generally speaking, it may permit one to turn a very hard-to-measure quantum A into an easier-to-measure quantum B.

It is probably important to add a reminder here that a measurement at the quantum level has a qualitatively different character than the usual magnetization measurement, in that it has an unavoidably "digital" character [13]. In short, if the wavefunction of the single spin is $\psi = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$, then a successful von Neumann measurement should announce the outcome "up" with probability $|\alpha|^2$, and outcome "down" with probability $|\beta|^2$. The laws of quantum mechanics do *not* permit a measurement to obtain the value of α itself (at least, not using just one shot of the measurement), as we would expect if we naively extrapolate the usual magnetization measurement down to the Bohr-magneton level. We will see how the measurement proposed below conforms to this "digital" rule.

[5] and [6] both invoke as the preamble to a quantum measurement such a reimbodiment, in particular, one which maps an electron *spin* quantum into an electron *charge* (or orbital) quantum state. This is a very desirable transformation, since there are known methods for performing electron-charge measurements with exquisite sensitivity, reportedly at sensitivity levels of 10^{-8} of one electron, using either a single-electron transistor [14] or a quantum point contact [15]. (Kane's scheme [6] requires concatenating this with another swap, one which takes a nuclear spin state to an electron spin state. I will not discuss this step here.)

How is this swap, involving a change of the carrier of the quantum bit state, to be achieved? We are helped some by the fact that since the transformation is to be immediately followed by a genuine measurement, we do not have to be extremely fussy about the maintenance of full quantum coherence during the swap; in fact, dephasing in the basis of the measurement will be entirely permissible. This permits us to consider incoherent dynamics, such as tunneling, to accomplish the desired swap.

Now I finally come to the specific ideas, which we have touched upon previously [4,5], for how to measure the spin of one electron. Figure 1 illustrates two versions of the basic idea. In both, a single electron is held inside a quantum dot, with its spin state being controlled by quantum gate operations; the control devices needed to perform these are not shown here [5]. We imagine these dots to be confined regions within a heterostructure quantum well formed in GaAs or Si/Ge structures, although other quantum dot implementations (for examples, those obtained by self-assembled growth) are possible too.

The key element of these structures is a layer, lying either above the quantum dot in the vertical structure, or in a trench interrupting the two-dimensional quantum well in the in-plane structure, of an insulating, magnetized material. While insulating ferromagnets are not so common (the spins in insulators tend to order antiferromagnetically), some are well known and have been studied extensively. For example, it was shown long ago [16] that the europium chalcogenides, in particular EuSe and EuS, can be grown in thin films which exhibit a strong "spin filter" effect [17–19], in which carriers of one spin orientation tunnel through the barrier preferentially between two metal electrodes. In favorable cases [19] the

spin polarization in tunneling has exceeded 99%.

We propose to exploit the "spin filter" property of such a barrier to accomplish the swap necessary to do the quantum measurement. As the figure shows, in the "measure" phase a gate voltage (or several of them) is changed so that the electron wavefunction is pressed against the magnetic barrier. The magnetization in the barrier produces an exchange splitting of the conduction band (known to be 0.36eV for EuS in zero applied magnetic field [17,20]), so that the barrier height for the two spin directions differs by this amount. If the band lineups are such that the low barrier is ≪0.36eV as indicated in Fig. 1, then conditions can be achieved such that spin-up has a very high probability of tunneling through the barrier, while spin-up has virtually none.

Thus, the desired interconversion has taken place. The measurement of spin up or down is converted to a measurement of whether the electron is on the left or the right of the barrier, or alternatively, whether the electron can pass repeatedly though the barrier or not. The latter suggests an a.c. capacitance measurement, as proposed by Kane [6]. In either case this becomes a problem in electrometry; many measurements of electric charge at the single-electron sensitivity level have now been done, either with single electron transistors [14], or with quantum point contacts [15]. We will not do any analysis of the requirements of this measurement here, but we note that an excellent study of the parameters required in an single-electron-transistor measurement for this application has been given in the context of superconducting quantum-box qubits [21].

Many of the parameters of the europium compounds which would be relevant to this measurement proposal are well known; EuO [20] and EuS are low temperature ferromagnets (Curie temperatures of 69K and 16.6K), while EuSe becomes ferromagnetic in a moderate applied field. The energy gaps for EuO and EuS are 1.1eV and 1.65eV, with localized f states forming the valence band; the conduction band is formed from delocalized d states, which makes the description of the tunneling of band electrons through the barrier of Fig. 1 valid. Of course, much is *not* known that would be needed for the present proposal: in particular, the compatibility of these magnetic materials with conventional semiconductors

like GaAs or Si or Ge is apparently unknown. The band lineups, epitaxy and quality of the interfaces, the nature of interface states, would all have to be understood for this idea to work. It may be that some other magnetic insulator, perhaps a transition metal oxide, would better fulfill the requirements of this proposal. I hope that workers in magnetic materials will be interested in conducting this possibly arduous search for a compatible materials system; the payoff for finding such a system would be undeniably great for physics.

ACKNOWLEDGMENTS

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vertical or in-plane
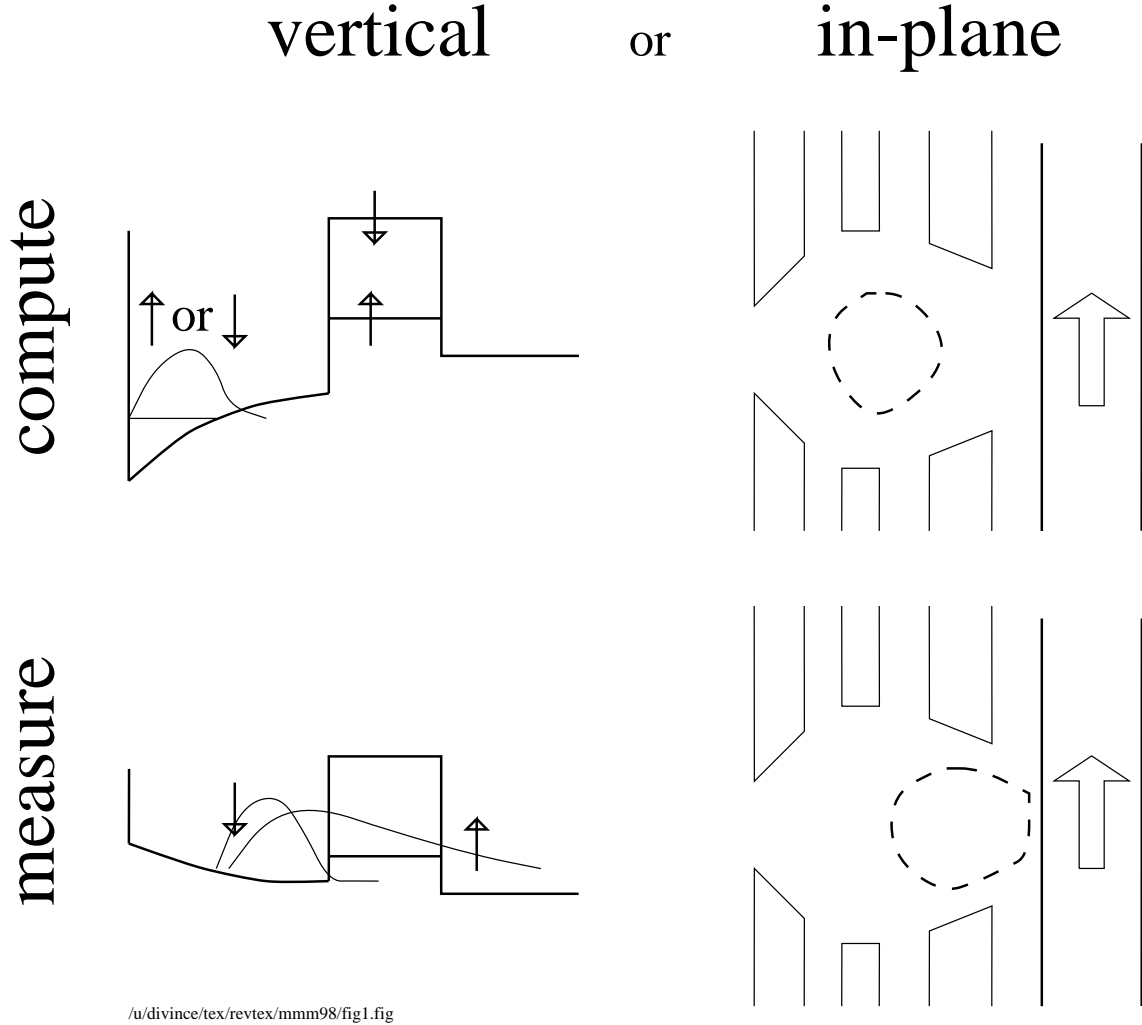
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FIG. 1. Schematics of the spin-filter quantum measurement. Possible vertical and in-plane structures are shown. In the compute phase the electron wavefunction in the quantum dot is held far away from the ferromagnetic insulator barrier. In the in-plane structure, the classical turning point of the quantum dot potential is shown dashed. In the measure phase the gate potentials are changed so that the electron wavefunction is pressed up against the ferromagnetic barrier. Because of the exchange splitting of the conduction electron barrier in the ferromagnet, spin up will tunnel through the barrier easily while spin down will not.